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Vanadium Redox Flow Battery

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181 VANADIUM REDOX FLOW BATTERY

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Brief technology description

Vanadium redox flow batteries also known simply as Vanadium Redox Batteries (VRB) are secondary (i.e. rechargeable) batteries. VRB are applicable at grid scale and local user level. Focus is here on grid scale applications.

VRB are the most common flow batteries. A flow battery consists of a reaction cell stack, where the electrochemical reactions occur, at least one storage tank filled with electrolyte (anolyte) consisting of reactants in solution for the negative battery electrode, i.e., the anode, at least one storage tank filled with electrolyte (catholyte) consisting of reactants in solution for the positive battery electrode, i.e., the cathode, piping connecting the storage tanks with the reaction cell stack, and mechanical pumps to circulate the electrolytes in the system. A schematic of a traditional flow battery can be seen in Figure 1. The region bordered by the grey electrodes is the reaction cell stack.

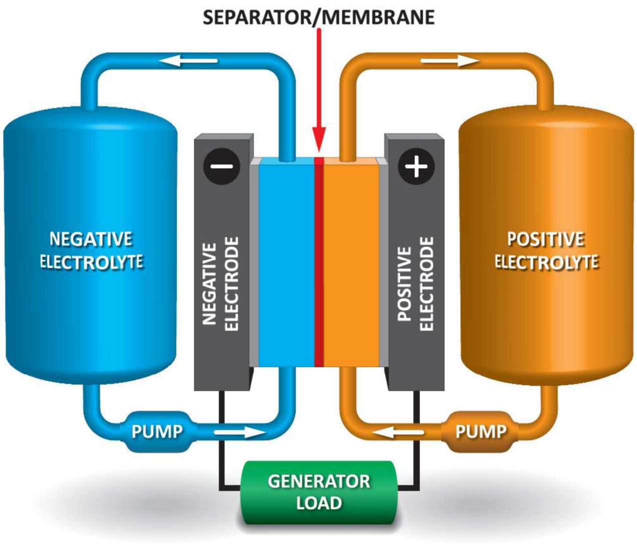

Figure 1: Schematic of flow battery [1].

The anolyte reactive species are V^{2+} and V^{3+} ions. The catholyte reactive species are VO_2^+ and VO^{2+} ions with the V atom in oxidation state +5 and +4, respectively. Traditionally, the reactive species have been dissolved with concentrations of 1.5 - 2 M in aqueous sulfuric acid solutions with an acid concentration of 2-5 M [2].

When pumped into the reaction cell the anolyte and catholyte will be separated by a proton conducting (polymer) membrane. An illustration of reaction cell components and a full reaction stack can be seen in Figure 2.

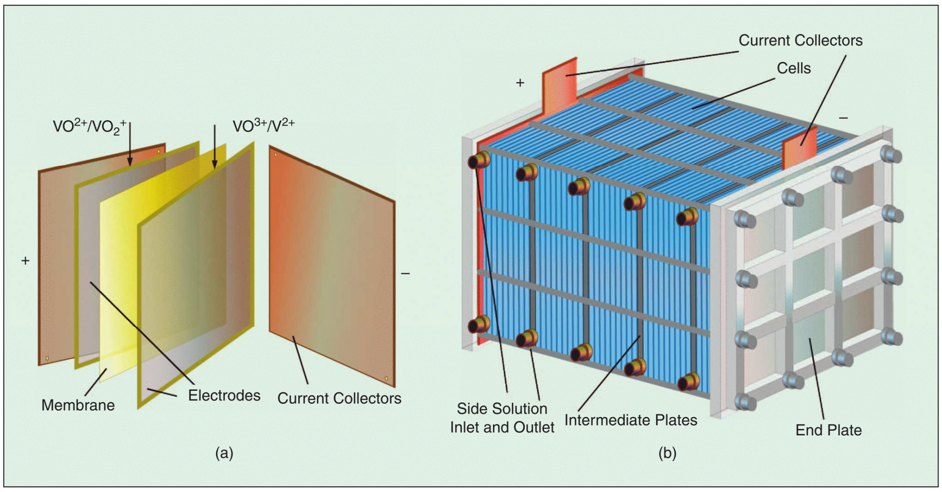

Figure 2: a) Reaction cell. b) Typical stack [2].

During discharge the following reaction occurs in the cell as two protons pass through the membrane and an electron pass through an external circuit.

$$V^{2+} \rightarrow V^{3+} + e^- \qquad \text{(Anode side reaction)}$$

$$VO_2^+ + 2H^+ + e^- \rightarrow VO^{2+} + H_2O \qquad \text{(Cathode side reaction)}$$

$$V^{2+} + 2H^+ + VO_2^+ \rightarrow V^{3+} + VO^{2+} + H_2O \qquad \text{(Full cell reaction)}$$

During charge the reverse reaction occurs. The full reaction provides a cell voltage of 1.26 V. The battery operates at ambient temperatures.

Flow batteries are different from other batteries by having physically separated storage and power units. The volume of liquid electrolyte in storage tanks dictates the total battery energy storage capacity while the size and number of the reaction cell stacks dictate the battery power capacity. The energy storage capacity and power capacity can thus be varied independently according to desired application and customer demand [2].

A VRB installation consists, as a minimum, of a VRB unit as described above, a battery management system, and a power conversion system connecting the battery unit to the grid. For a more detailed technology description the reader is referred to “Encyclopedia of Electrochemical Power Sources” [3].

Input/output

Primary input and output are both electricity. Electricity is converted to electrochemical energy during charge and converted back to electricity during discharge in the reaction process described above.

Energy efficiency and losses

Electrolyte left in the cell stack during idle periods will self-discharge over time resulting in an energy loss. As the electrolyte volume in the cell stack is generally small compared to the total electrolyte volume, the total energy loss from self-discharge will be at most 2 % of stored energy during any idle period [4]. The mechanical pumps require energy. The energy used by the mechanical pumps is included in determination of battery efficiency and should thus not be treated as a separate loss.

For individual VRB reaction cells the energy conversion efficiency can be as large as 90 % at low current densities [3]. The grid-to-grid efficiency is reported by multiple sources to be approximately 70 % at constant rated discharge power [1], [4], [5]. UniEnergy Technologies reports 75 % energy efficiency for frequency regulation application and 70 % energy efficiency for peak shaving application [6]. Vionx Energy reports a DC efficiency of 78 % and an AC efficiency of 68 % for their units operating at rated capacity [5].

Regulation ability and other system services

The response time (i.e. the time it takes for the battery to supply a requested charge or discharge power) is according to manufactures < 100 ms if electrolyte is already present in the reaction cell [4], < 1 s if electrolyte must first be pumped into the cell [5], and < 1 min if the pumps are turned off [5]. Large scale VRB installations have been demonstrated to be routinely capable of operating for 30 s at 150 % rated power capacity [7].

Grid scale battery operation depends on the application. Batteries used for time shifting will generally complete a single charge/discharge cycle over 24 hours. Batteries used for various other grid services including stabilization of input from renewables as exemplified below will often not undergo traditional battery cycling but frequently switch between being charged and discharged according to demand.

Due to its short response time combined with the ability to independently vary installation size of energy storage capacity and power capacity, VRB installations can provide a range of system services. The manufacturer UniEnergy Technologies lists the following applications for grid and utility installations: T&D deferral (avoid need to upgrade transmission and distribution equipment), flex capacity/ramping, load shifting, and ancillary services [6].

Typical characteristics and capacities

Examples of recently commissioned grid-scale VRB installations are listed Table 1.

Location	**Yokohama, Japan**	**Hokkaido, Japan**	**Braderup, Germany**	**Pullman, Washington, USA**
Commissioning year	2012	2016	2014	2015
Energy Storage Capacity	5 MWh	60 MWh	1 MWh	4 MWh
Power Capacity	1 MW	15 MW	325 kW	1 MW
Technology provider	Sumitomo Electric Industries	Sumitomo Electric Industries	UniEnergy Technologies	UniEnergy Technologies

Table 1: Selected grid-scale VRB installations [6], [8], [9].

The non-exhaustive DOE Global Energy Storage Database [1], [9] lists 21 different installations of at least 100 kW commissioned since 2011. The 21 installations have been supplied by at least 8 different manufactures. A 200 MW/800 MWh installation is currently under construction in Dalian in China [9].

The energy density and specific energy for two selected commercial units are shown in Table 2.

Manufacturer	Energy density (Wh/m^3)	Specific energy (Wh/kg)
UniEnergy Technologies	9040	11.8
Sumitomo Electric Industries	5880	7.1

Table 2: Energy density and Specific energy for commercial VRB units [4], [10].

Typical storage period

The typical storage period depends on operation. It ranges from minutes to hours for grid scale installations [11]. The storage time is not technologically limited. Energy can be stored for extended periods of time as is the case in small local user level VRB units used for emergency power.

Space Requirement

The installation in Hokkaido, Japan (Table 1) commissioned in 2016 occupy a total land area of 5000 m^2 [12]. This corresponds to a land use of 83.3 m^2/MWh.

UniEnergy Technologies have in promotional material suggested that an installation with 240 MWh storage capacity would occupy a land area of 4000 m2 [6]. This corresponds to a land use of 16.7 m2/MWh. This is the lowest value found.

The largest land usage found for current commercially available grid scale VRB units is 140.2 m^2/MWh [10].

Advantages/disadvantages

General advantages and disadvantages of batteries in comparison to other technologies for energy storage are listed in Table 4.

Advantages	Disadvantages
Short response time	
Flexible installation size	Relatively short lifetime[12]
High energy efficiency	
Versatile application	Large investment cost
Relatively compact	
Low maintenance	

Table 4: General advantages and disadvantages of batteries in comparison to other technologies for energy storage

In comparison to other grid-scale batteries, VRB and other flow batteries have the significant advantage that the energy storage capacity and power capacity can be varied independently and optimized for a specific application. In contrast to molten sodium batteries (Na-S and $Na\text{-}NiCl_2$) also applicable for grid scale applications, VRB operate at ambient temperatures. The reactants in a VRB are in a solution. This allows the full energy storage capacity of the battery to be utilized without battery degradation in contrast to batteries where charge/discharge products are solid state [1]. VRB have long technical lifetime in comparison to other batteries. Current batteries are reported by multiple manufactures to have unlimited cycle lifetime within the technical lifetime (up to 20 years). Due to the large technical and cycle lifetime compared to other batteries, VRB have the lowest levelized cost of storage (€/kWh per cycle) among grid scale batteries [2]. VRB also have the advantage that the electrolytes can easily be recycled and reused [1]. As vanadium is the active specie in both anolyte and catholyte, leakage of reactants from one electrolyte into the storage container of the other electrolyte will, in contrast to other flow batteries, not result in electrolyte contamination but only loss of energy storage capacity. The energy storage capacity can be regained by re-balancing the volume and vanadium content of the two electrolyte solutions [1]. VRB are by manufactures promoted as being very safe [6].

VRB and other flow batteries have relatively low grid-to-grid energy efficiencies in comparison to other batteries. This is a consequence of losses related to mechanical pumping of electrolyte, undesired electrical currents known as shunt currents, which allows electrons to bypass the external circuit, and leakage of reactant vanadium ions through the reaction cell membrane. Even though the energy density and specific energy for VRB have recently increased, they remain relatively low in comparison to other batteries [1], [13]. The cost of

[12] Although some batteries have lifetimes as long as 20 years (VRB), battery lifetimes in general are shorter than that of PHS (60 years) and CAES (50 years) [28] .

vanadium has historically been high and have recently increased by approximately 50 % [14], [15]. The raw material cost of vanadium has previously been estimated to contribute $140/kWh to the battery cost, which corresponds to approximately 20 % of the total investment costs for a VRB installation [16]. The absolute minimum energy storage capacity cost of VRB with the currently used reaction chemistry is approximately 70 $/kWh, assuming a cost of V_2O_5 at 6 $/lb [17] is used as source of vanadium [18]. The future cost of vanadium might be higher. Currently, demand exceeds supply and prices have increased to approximately 9 $/lb for V_2O_5 [14], [15].

R&D can and has previously allowed lower-cost sources of vanadium to be used as raw material [1]. The vanadium reactants have the potential to corrode the membrane. High quality and large cost membranes must thus be used in VRB reaction cells [1], [13]. Alternatively, the membrane must be replaced within the technical lifetime of the battery.

Environment

The active reactants in VRB are vanadium ions. Besides being relatively expensive, vanadium might also pose environmental risk factors, which are yet to be fully determined [19]. Most VRB components can be recycled [1]. The vanadium electrolyte is if possible directly reused. Otherwise the vanadium is extracted before further disposal or recycling [1]. Some of the initial investment into raw material vanadium might be regained in this process. The cell membranes might be highly acidic or alkaline after end of battery life and should thus be treated as corrosive material during recycling or disposal [19].

Research and development perspectives

VRB are under rapid development. There is significant potential for R&D to reduce cost of all battery components [20], [21]. An example is research in use of non-aqueous electrolytes [2]. The minimum cost will, however, likely be limited by the vanadium cost. The vanadium cost is not fixed in the sense that there is a potential for use of lower cost vanadium sources in production than those traditionally used [1].

There is a significant potential for cost reduction of flow batteries by using alternative reaction chemistries, i.e., other redox couples than vanadium [21]. Grid scale redox flow batteries could potentially be based on, e.g., zinc-bromide, bromide-polysulphide, iron-chromium, and zinc-chloride [21].

Examples of market standard technology

Grid scale turn-key VRB installations are commercially available from several currently operating manufactures as shown in the non-exhaustive list in Table 5. The market appears volatile with VRB manufactures frequently entering the market or ceasing to operate.

Manufacturer	Website
Gildemeister Energy Solutions	http://www.energy.gildemeister.com/en
REDTEnergy	http://www.redtenergy.com
Rongke Power	http://www.Rongkepower.com
Sumitomo Electric Industries	http://global-sei.com/
UniEnergy Technologies	http://www.uetechnologies.com/
Vionx Energy	http://www.Vionxenergy.com

Table 5: Some currently operating VRB manufactures.

The Danish company VisBlue (http://www.visblue.com) provides VRB installations marketed for local users of up to 100kW/500kWh in size.

Two examples of standard units are presented below. Performance data for the Uni.System unit manufactured by UniEnergy Technologies is listed in Figure 3. A Uni.System unit consists of 5 standard 20 foot containers [6]. Data for VNX1000 type units with variable energy storage capacity is listed in Figure 4.

UNI.SYSTEM™ (AC) PERFORMANCE DATA

Peak Power	600 kW_{AC}		
Maximum Energy	2.2 MWh_{AC}		
Discharge time	2h	4h	8h
Power	600 kW_{AC}	500 kW_{AC}	275 kW_{AC}
AC (Roundtrip) Efficiency	≈70%		
Voltage	12.47kV +/- 10%		
Current THD (IEEE 519)	<5%THD		
Response Time	<100ms		
Reactive Power	+/- 450kVAR		
Humidity	95%RH noncondensing		
Footprint	820 ft^2 ($76m^2$)		
Envelope	41'[W] x 20'[D] x 9.5'[H] (12.5m[W]x6.1m[D]x2.9m[H])		
Total Weight	375,000 lbs (170,000 kg)		
Cycle and Design Life	Unlimited cycles over the 20 year life		
Ambient Temp.	-40°F to 122°F (-40°C to 50°C)		
Self Discharge	Max 2% of stored enegy		

Figure 3: Performance data for Uni.System unit [4].

ENERGY STORAGE MODULE	VNX1000-6	VNX1000-8	VNX1000-10
Energy Storage (MWh)	6 MWh	8 MWh	10 MWh
Usable Depth of Discharge	100%	100%	100%
Life		20 years (unlimited cycles)	
Power Rating		1 MW AC (2 Stack Containers)	
DC Footprint	185 m² / 2,000ft²	195 m² / 2,100ft²	205 m² / 2,200ft²
DC Efficiency (stack)	78%	78%	78%
DC Voltage		500V—800V DC operating range	
AC Efficiency	68%	68%	68%
Signal Response		<1 Second electrolyte pumps ON <1 Minute electrolyte pumps OFF	
Interconnection Standard		IEEE 1547	
Operating Ambient Temperature		-40°C to +45°C / -40°F to 113°F	
Relative Humidity		0 to 100%	

Figure 4: Data for various VRB configurations from Vionx [5].

Prediction of performance and cost

Data for 2015

The balance between power capacity and energy storage capacity in battery installations, which for flow batteries at least in principle can be adjusted according to customer demand, will influence the "energy component" cost, as it is defined here. The ratio can be quantified through the discharge time at rated power, *h*. The cost of the battery including electrolyte storage and reaction stack per MWh, i.e., the energy component in the data sheet below, is given by

$$C_E = C_{elec} + C_{stack} / h$$

where C_{elec} is the cost of electrolyte and storage tanks and C_{stack} is the cost of the reaction stack and other parts of the system including pumps. According to IRENA [22], C_{elec} = 347 €2016/kWh and C_{stack} = 1313 €2016/kW. A similar reaction stack cost has previously been found [23]. Thus

$$C_E = 347\ \text{€/kWh} + 1313\ \text{€/kW} \ / \ h$$

O&M costs are obtained from Carlsson et al. [24] (assumed similar to 2013 values), and Zakeri and Syri [25].

Previously, the membrane in the reaction stack has required replacement after approximately 8 years of use [26]. This does, however, not appear to be the case in all currently available technological designs [6].

Assumptions for the period 2020 to 2050

Estimates for 2020 and 2030 in the data sheet below are based on data from IRENA [22], [27], [28]. Values in USD have been converted to € using an exchange rate of 0.86.

As discussed in the Chapter Electricity Storage, the current PCS cost including grid connection is 0.4-0,5 M€/MW. This is used as reference value for the "capacity component". The inverter costs, which account for approximately 50 % of cost [19], [25], [29], is predicted to decrease by 20 in 2020 % and 50 % in 2030 [22], [27]. The other 50 % of cost is assumed constant. Cost reductions of capacity components is assumed to not occur beyond 2030.

2050 financial figures predicted from learning curves have previously found cost reductions of 7.5 % from the period 2030 to 2050 for the cost per power capacity [30]. Although power and energy storage capacity will likely not follow identical development in cost, the 7.5 % cost reduction is assumed to apply to both. This neglects the possibility that the raw material cost of vanadium might increase.

"Other project costs" is assumed to be 8 % of CAPEX (here "Specific investment"), as per data from EPRI [19].

O&M costs are assumed to be constant in the given units.

No development in calendar lifetime, and efficiency is assumed to take place beyond 2030. The regulatory ability is assumed to not improve.

Learning curves and technological maturity

The level of maturity for grid scale VRB is early "Category 3: Commercial technologies with moderate deployment". Based on the current commercial situation with large market volatility it is difficult to establish general learning curves based on past installations. It has been attempted [18]. The reported uncertainties are, however, of a magnitude making the predicted price range 120-1,160 US$/kWh by 2040. The approach of IRENA [22], [27], [28] is thus preferred for predictions.

Uncertainty

Uncertainties for 2020 and 2030 are when possible obtained from IRENA [22], [28]. Uncertainties in 2050 are assumed to be percentagewise similar to those in 2030. For the "capacity component" the maximum values for PCS cost found by Zakeri and Syri [25] are used as baseline. The uncertainties are calculated for future years by keeping the relative uncertainty compared to the cost prediction constant.

The uncertainties for O&M costs are determined using the literature review by Zakeri and Syri [25]. The uncertainties are calculated from the expected value using the relative difference between the extrema and the average in the literature review. Uncertainties are in general large.

Additional remarks

Since battery units are highly modular and equipment is the main cost of full installations, a close to linear scaling in total cost vs. installation size is expected from a technological point of view. Significant financial benefits from increasing installation sizes will rely on negotiations with manufacturers.

Even though VRB and other flow batteries have high commercial potential, rapid cost reduction of alternative storage solutions, e.g., Li-ion batteries might halter commercial deployment and technological development of VRB and other flow batteries. This can prevent VRB and other flow batteries from reaching full commercial potential

Quantitative description

Technology	Vanadium Redox Battery (VRB)									
	2015	2020	2030	2050	Uncertainty (2020)		Uncertainty (2050)		Note	Ref
Energy/technical data					Lower	Upper	Lower	Upper		
Form of energy stored	Electricity									
Application	System, power- and energy-intensive									
Energy storage capacity for one unit (MWh)	2.0	2.0	2.0	2.0	0.4	800	0.4	800	A,M	[4]+[9]
Output capacity for one unit (MW)	0.5	0.5	0.5	0.5	0.1	200	0.1	200	A,M	[4]
Input capacity for one unit (MW)	0.5	0.5	0.5	0.5	0.1	200	0.1	200	A,M	[4]
Round trip efficiency - DC (%)	78	78	78	78	62	88	67	95	B	[5];[22]
- Charge efficiency (%)	-	-	-	-	-	-	-	-		
- Discharge efficiency (%)	-	-	-	-	-	-	-	-		
Energy losses during storage (%/day)	0	0	0	0	0	0.2	0	0.2	C	[4];[22]
Forced outage (%)	0.5	0.5	0.5	0.5	0	5	0	5	D,M	[1]
Planned outage (weeks per year)	0	0	0	0	0	0	0	0	D,M	[1]
Technical lifetime (years)	20	20	20	20	6	23	8	32		[4];[28]+[22]
Construction time (years)	1	1	1	1	0.2	2	0.2	2	E,M	[9]
Regulation ability										
Response time from idle to full-rated discharge (sec)	0.1	0.1	0.1	0.1	0.005	2	0.005	2	F,G	[4]+[30]
Response time from full-rated charge to full-rated discharge (sec)	0.07	0.07	0.07	0.07	0.004	1.4	0.004	1.4	F,G,M	[1]
Financial data										
Specific investment (M€2015 per MWh)	0.75	0.60	0.35	0.33	0.53	1.15	0.30	0.58	H	[22]+[27]/[19]
- energy component (M€/MWh)	0.58	0.45	0.24	0.22	0.38	0.94	0.19	0.44	H, I	[22]+[27]
- capacity component (M€/MW)	0.45	0.41	0.33	0.33	0.43	0.48	0.35	0.39	H	[22]+[25]+[27] /[19]
- other project costs (M€/MWh)	0.06	0.05	0.03	0.03	0.04	0.09	0.02	0.05	J	[19]
Fixed O&M (% total investment)	2.0	2.0	1.5	1.5	0.8	4.1	0.6	3.1		[24]+[25]/[2]
Variable O&M (€2015/MWh)	0.9	0.9	0.9	0.9	0.2	2.8	0.2	2.8		[25]/[2]
Technology specific data										
Alternative Investment cost (M€2015/MW)	3.0	2.4	1.4	1.3	2.1	4.6	1.2	2.3	H	[22]+[31]+[27] /[19]
Lifetime in total number of cycles	-|-	-|-	-|-	-|-	-|-	-|-	-|-	-|-	K	[1]
Specific power (W/kg)	2.9	2.9	2.9	2.9	1.45	3.63	1.45	3.63	A,L,M	[4]
Power density (W/m3)	2260	2260	2260	2260	1130	2825	1130	2825	A,L,M	[4]
Specific energy (Wh/kg)	11.8	11.8	11.8	11.8	5.90	14.75	5.90	14.75	A,L,M	[4]
Energy density (Wh/m3)	9040	9040	9040	9040	4520	11300	4520	11300	A,L,M	[4]

Notes:

A One Uni.System unit from UniEnergy Technologies. Installation sizes vary from tens of kW to hundreds of MW.

B Efficiency varies depending on use.

C Energy losses depend on idle situation. If pumps are off and electrolyte not present in the reaction stack no energy loss occurs. This increases response time (see above). Self-discharge only occurs for electrolyte inside the reaction stack. This is a relatively small volume and the self-discharge will be at most 2 % over time for typical installations. Losses related to stand-by energy consumption of pumps are not included.

D Some companies guarantee at least 99.5% uptime.

E Depends highly on the installation.

F Time is less than 100 ms for idle situation with electrolyte in reaction stack and pumps on [4]. Less the 1 s if electrolyte must first be pumped [5]. Less than 1 min if pumps are not on [5]. PCS might be limiting the response time.

G Might in practice be limited by PCS.

H Valid for installations with rated discharge times of 4 hours. Use equation in “Prediction of performance and cost” above to calculate for installations with a different rated discharge time.

I Composed of both electrolyte etc. at 347 €/kWh and stack at 1313 €/kW [22].

J Value for utility T&D installations with discharge time of 4 hours used.

K Manufactures state unlimited number of cycles during technical lifetime [4], [5].

L Varies with capacity to storage ratio. Is significantly lower for some manufactures.

M Uncertainties are based on a qualified guess.

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